Exploring **Extremely Dense** Medim in Heavy-Ion Collisions

Masakiyo Kitazawa
(Osaka U.)

NN2018, Omiya, Japan, 2018, Dec. 5

Relativistic Heavy-Ion Collisions

RHIC (2000~)
QGP Formation
Strongly coupled QGP

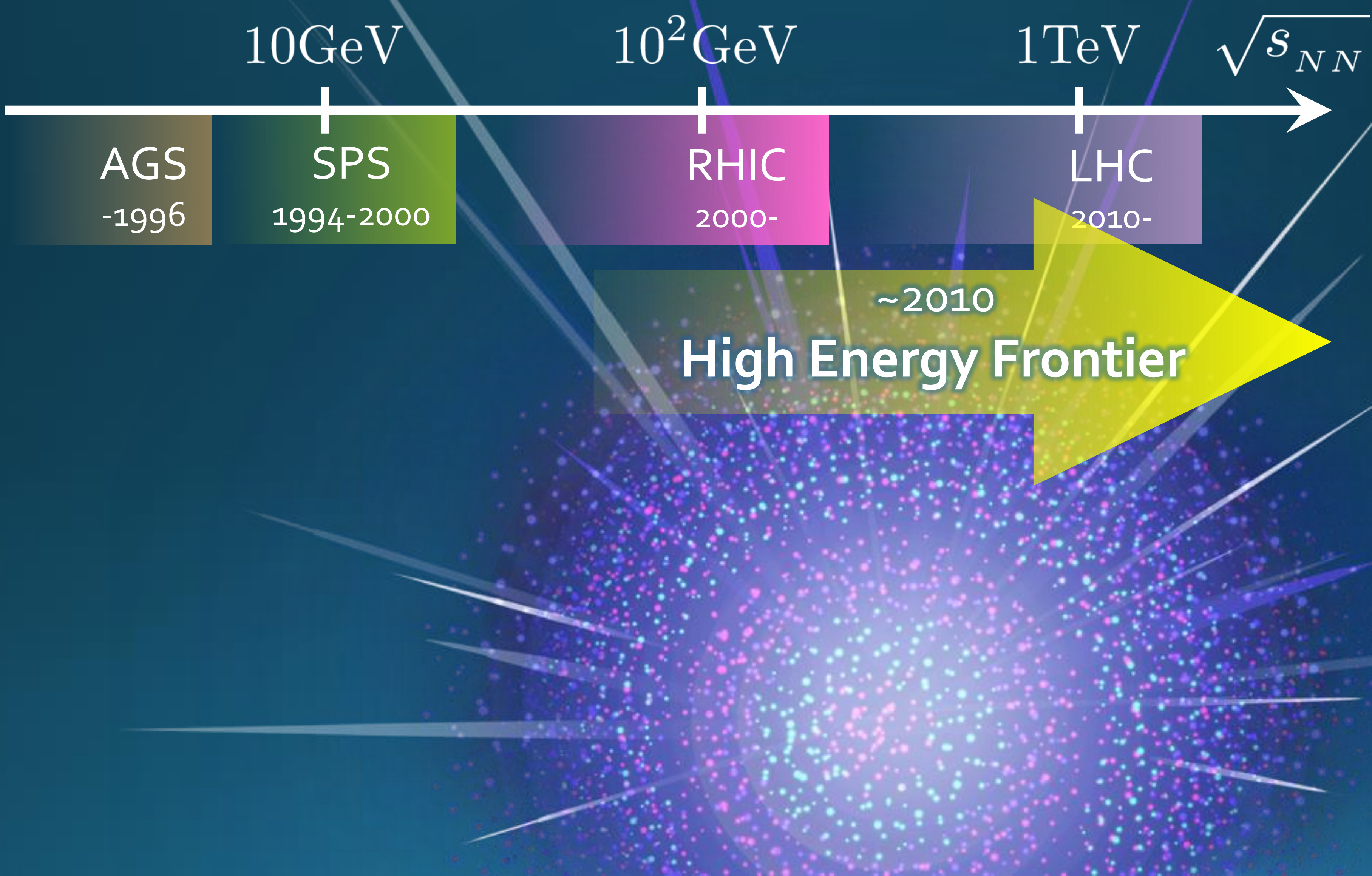
LHC (2010~)
Precision measurement of the QGP

Physics

- ☐ Hot & dense medium
- ☐ Early Universe
- ☐ Quark-gluon plasma
- ☐ QCD phase structre

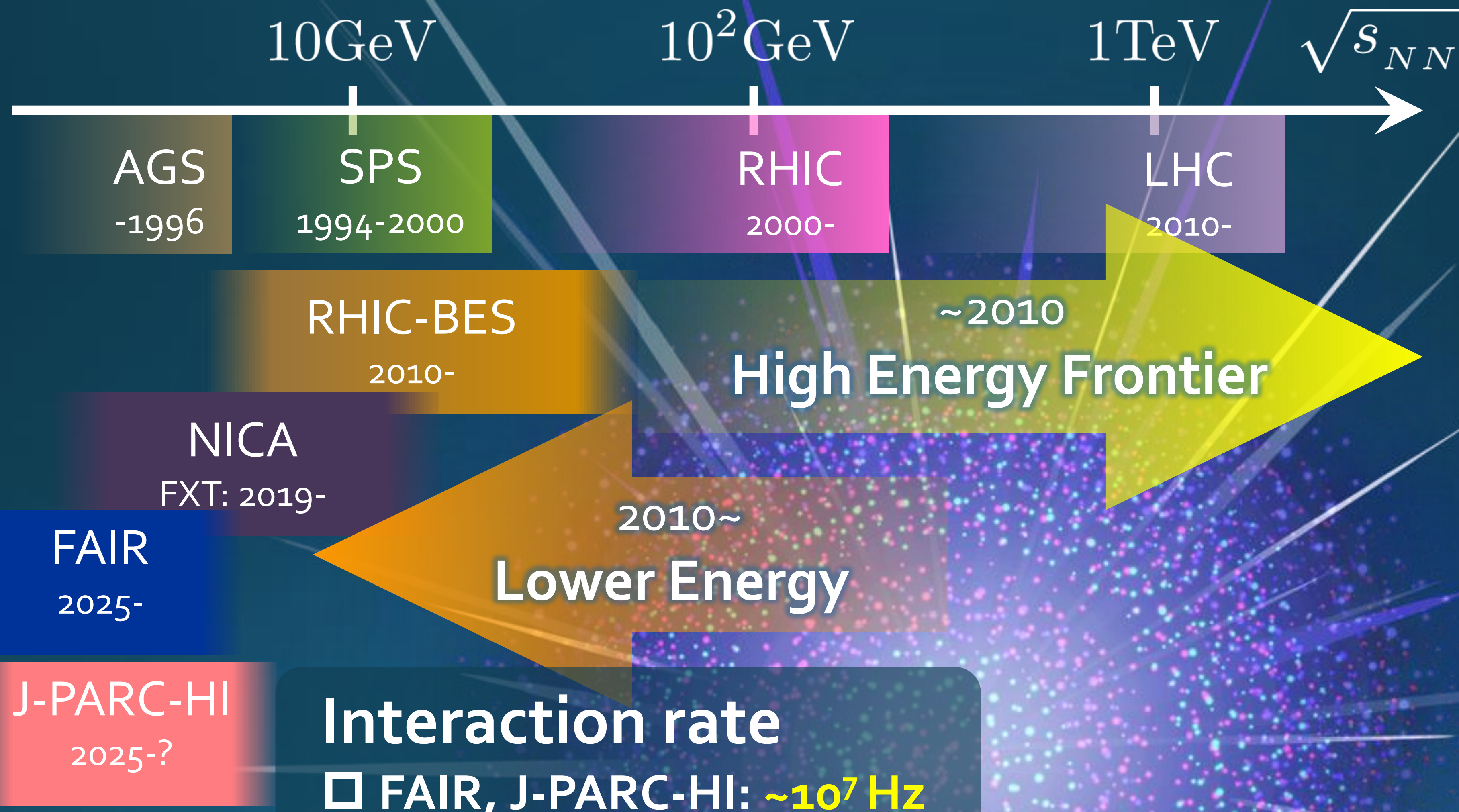
Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC



Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC

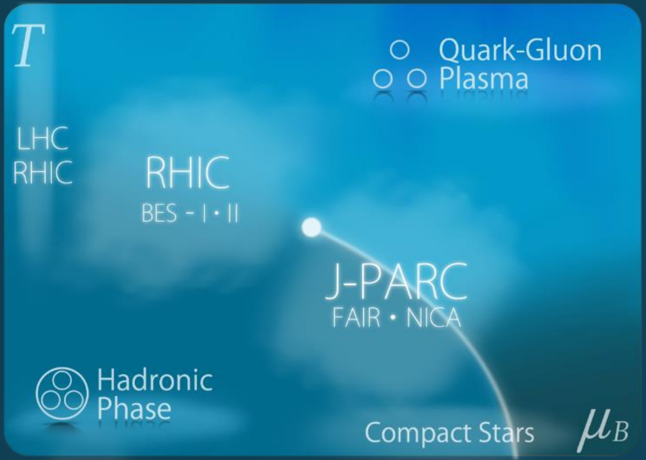


Interaction rate

- **FAIR, J-PARC-HI: ~10^7 Hz**
- AGS, SPS: ~10^2 Hz

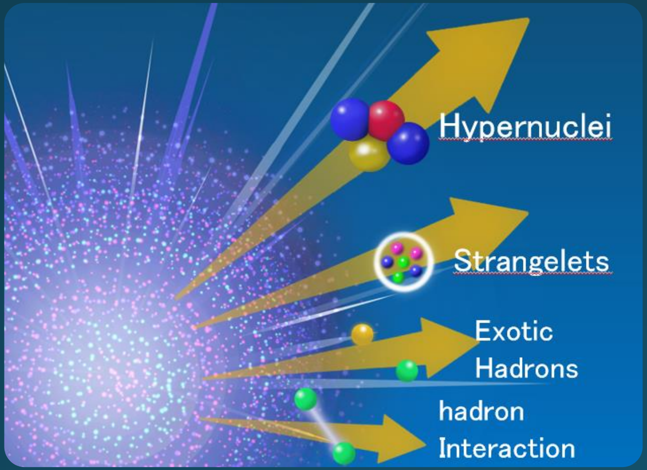
Picture of fireball by Soushi Nonaka

2 Main Goals



Exploring Dense Medium

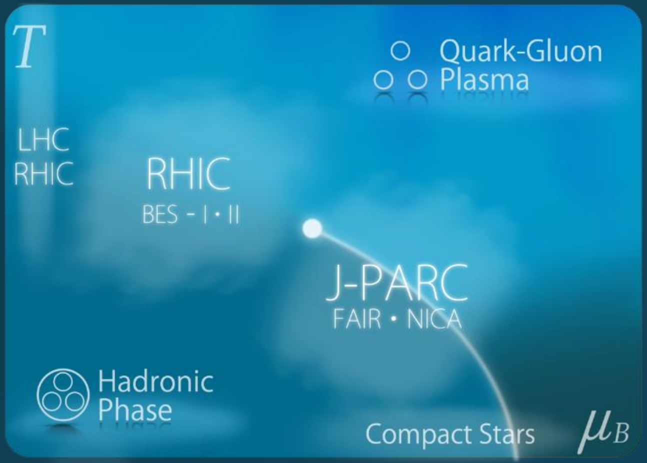
- ☐ QCD phase diagram
- ☐ 1st order phase transition
- ☐ equation of state



Rare-event Factory

- ☐ hyper nuclei
- ☐ exotic hadrons
- ☐ hadron interaction

2 Main Goals



Exploring Dense Medium

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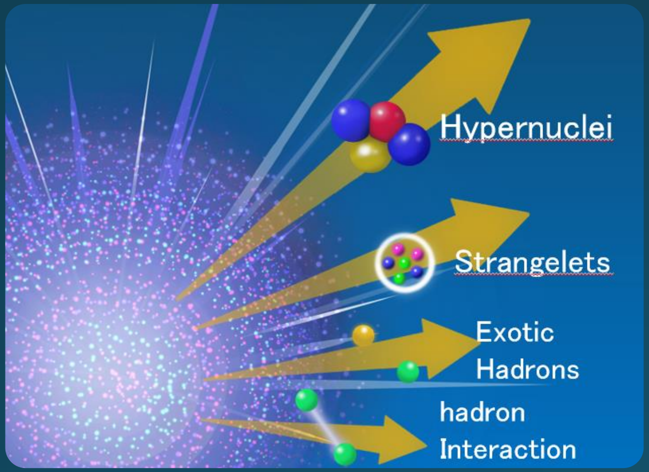

Rare-event Factory

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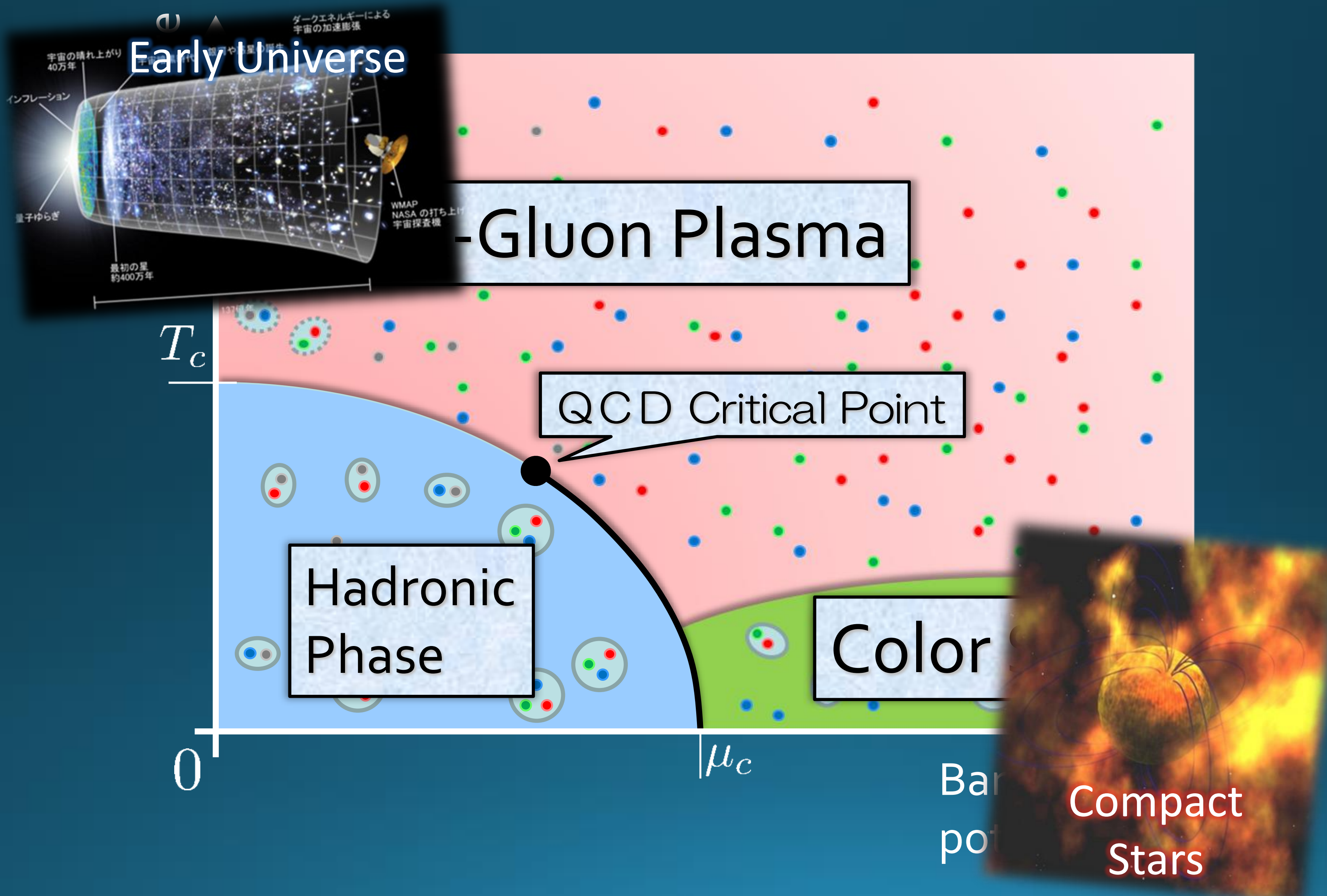
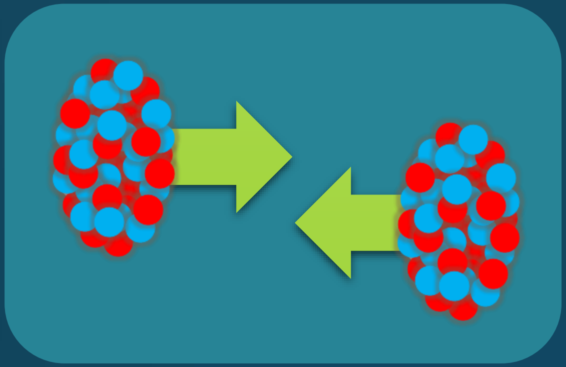
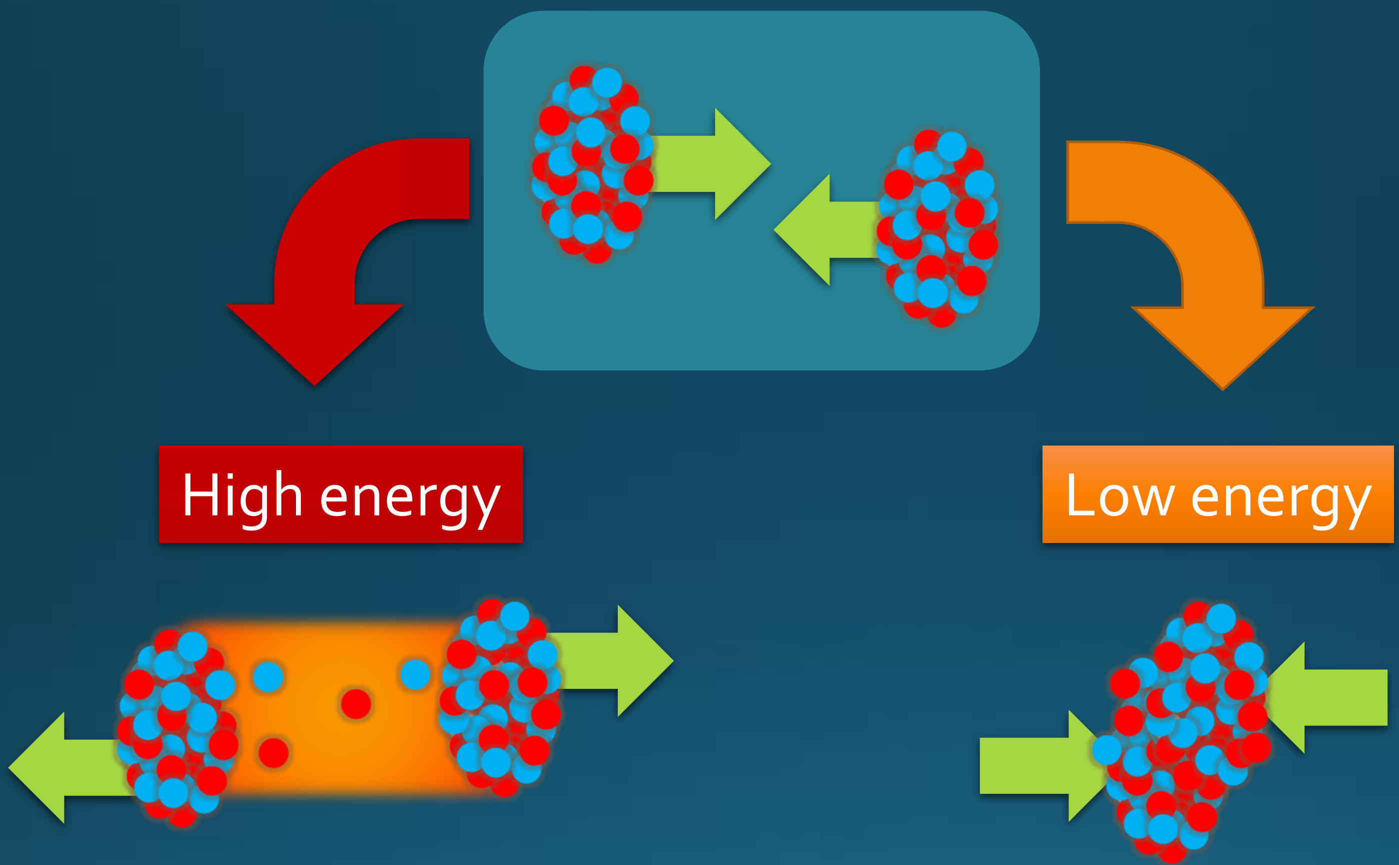
QCD Phase Diagram



Baryon Stopping



Baryon Stopping



Nuclear transparency

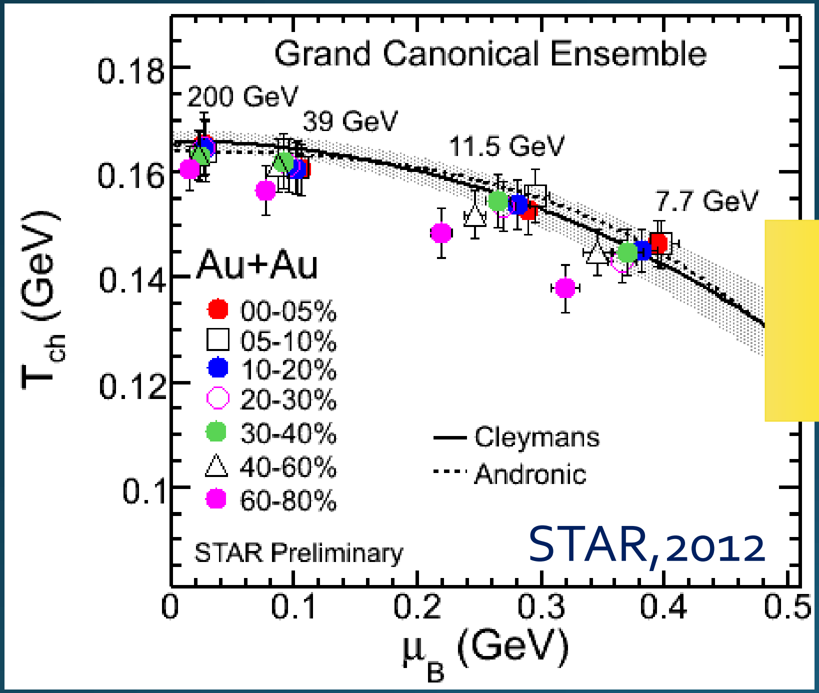
net-baryon #: small

Baryon stopping

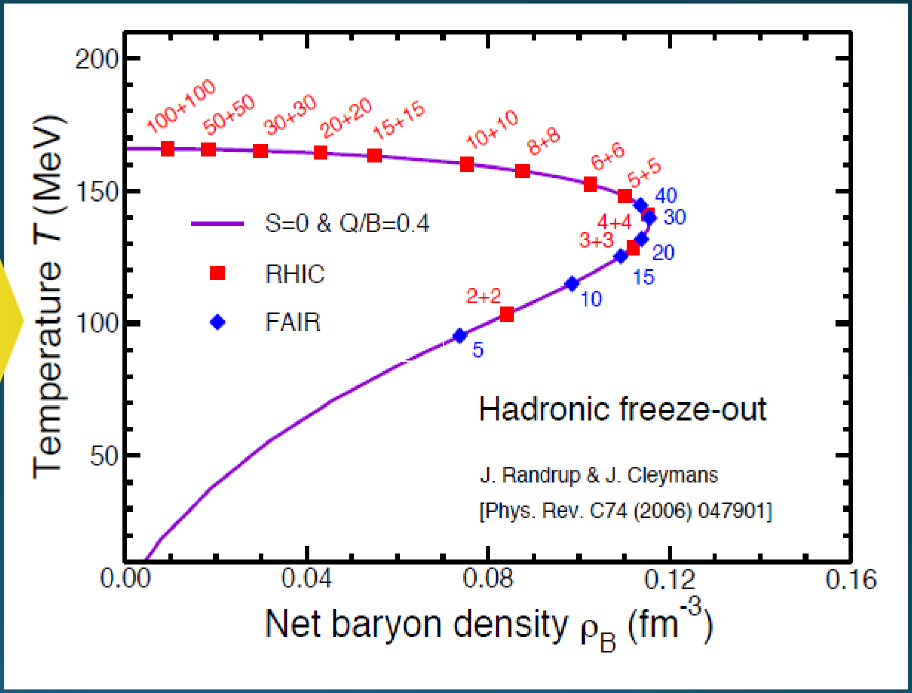
net-baryon #: large

Beam-Energy Scan

T, μ from particle yield



Translation to baryon density

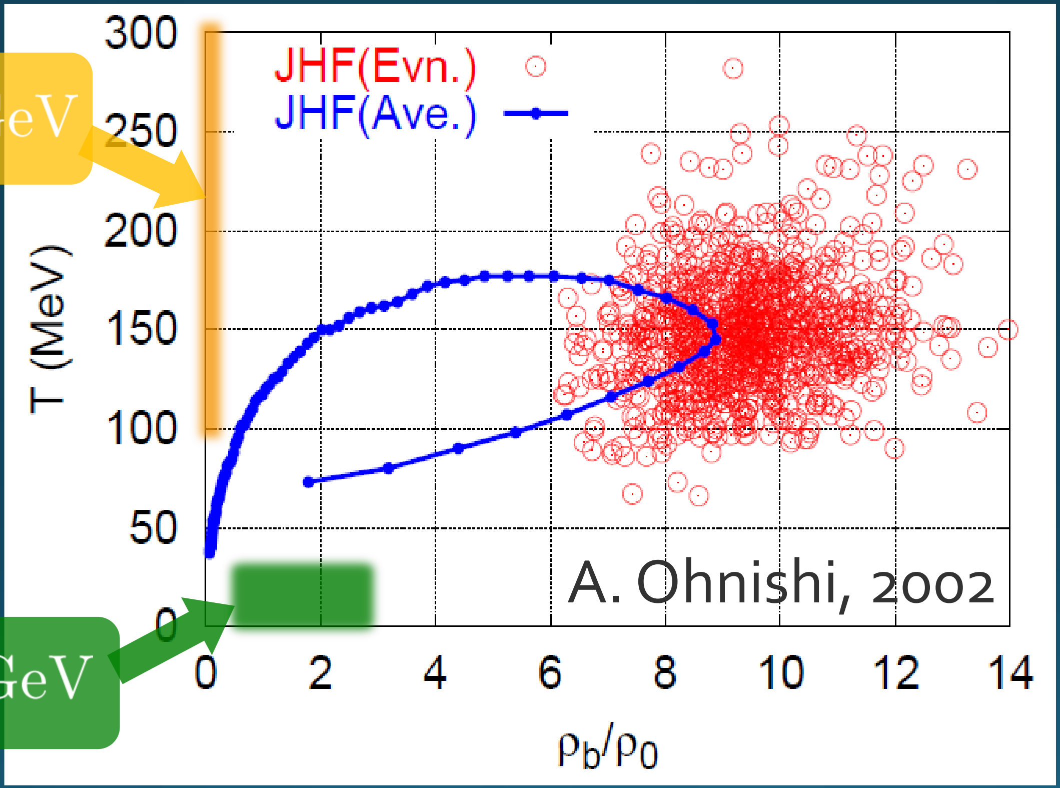


Highest baryon density

$$\sqrt{s_{NN}} = 3 \sim 8\text{GeV} \quad (E_{\text{lab.}} = 15 \sim 100\text{AGeV})$$

Maximum Density

Time evolution in *T*-ρ plane by JAM



$\sqrt{s_{\rm NN}} > 100$ GeV

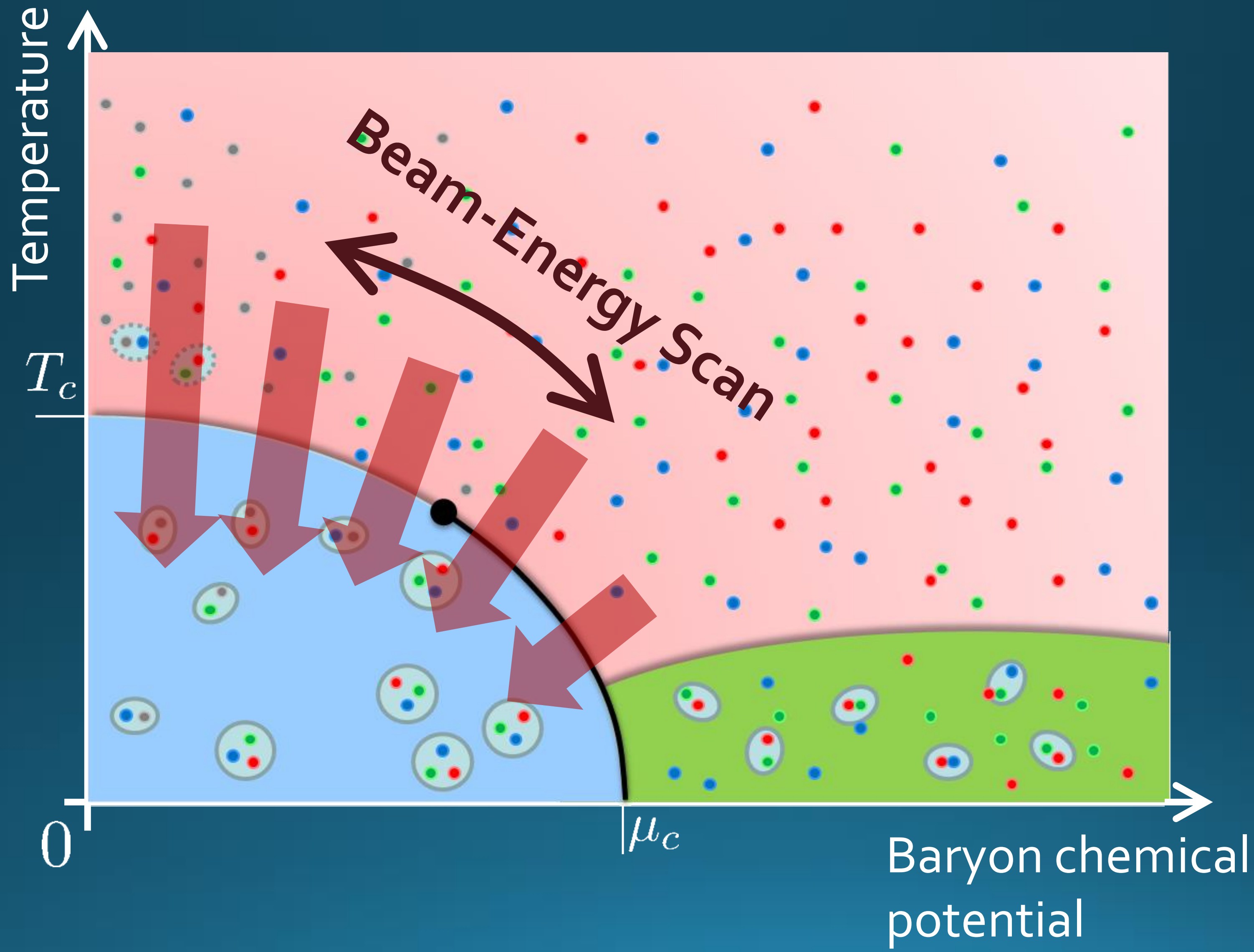
$E/A < 1$ GeV

$E/A = 20\mathrm{GeV}$

$\sqrt{s_{NN}} \simeq 6\mathrm{GeV}$

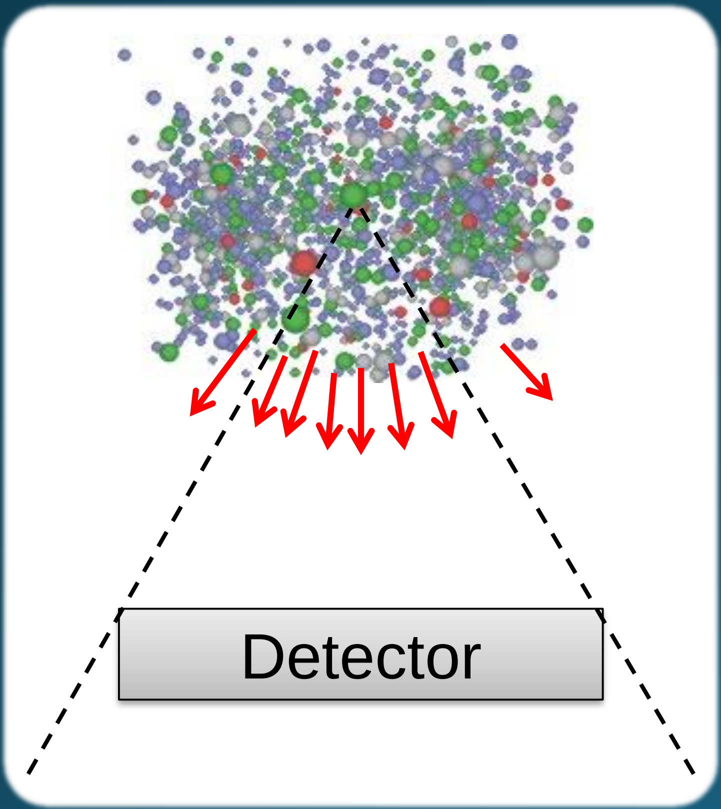
- ☐ Maximum density 5~10ρ_0 @ E/A~20GeV
- ☐ Large event-by-event fluctuations?

Beam-Energy Scan

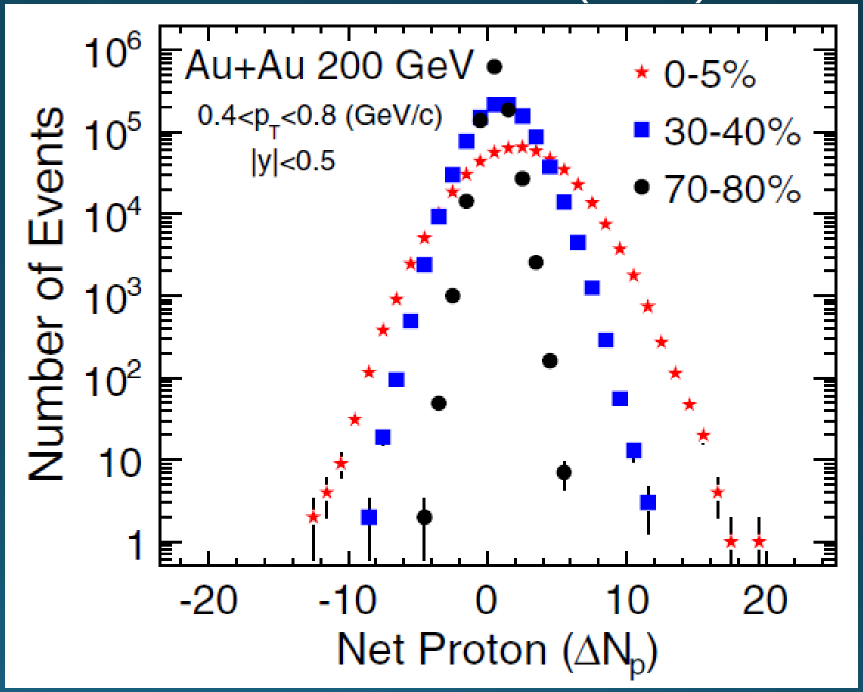


Event-by-Event Fluctuations

Review: Asakawa, MK, PPNP **90** (2016)



STAR, PRL**105** (2010)



Cumulants

$$\langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c$$

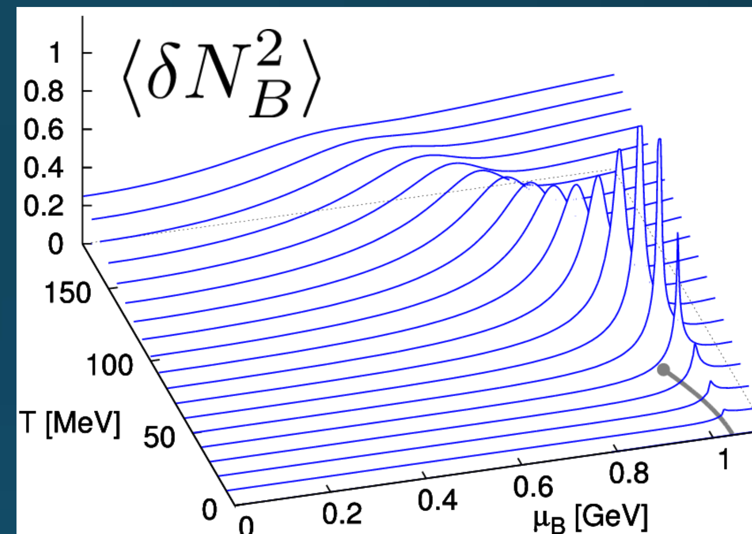
Non-Gaussian Cumulants

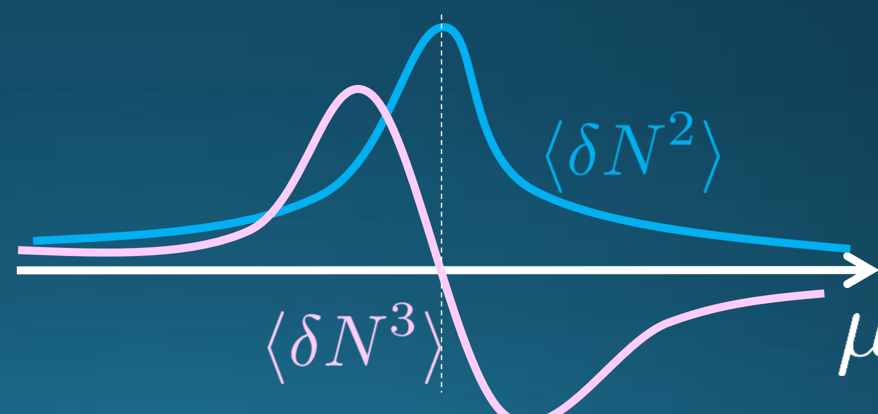
Gaussian fluctuations diverge at the QCD-CP

- ☐ Higher order cumulants change sign at the phase boundary

$$\langle \delta N^3 \rangle = T \frac{\partial \langle \delta N^2 \rangle}{\partial \mu}$$

Asakawa, Ejiri, MK, 2009

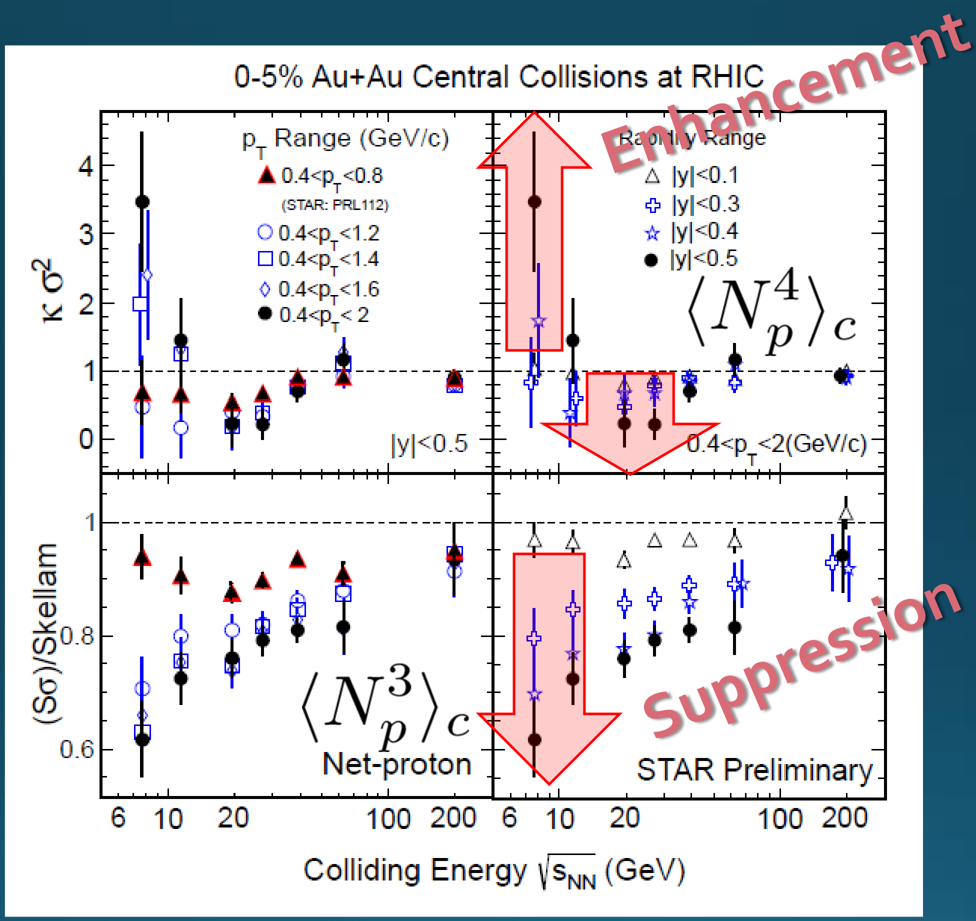




- ☐ Steeper divergence for higher-order cumulants

Stephanov, 2009

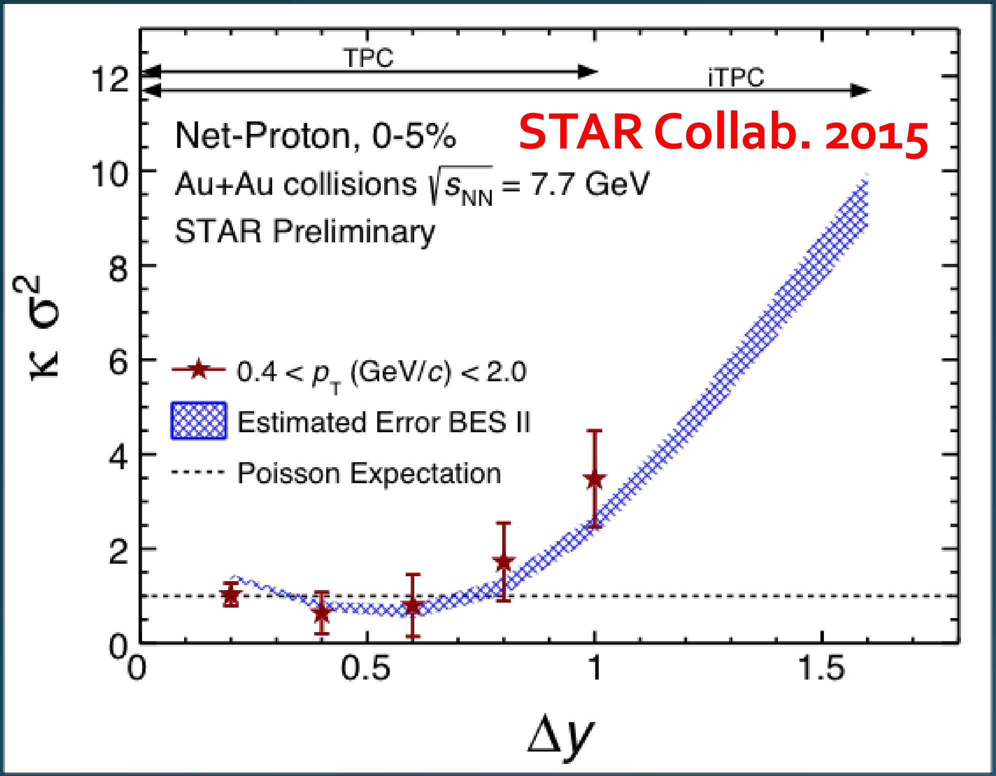
Experimental Results

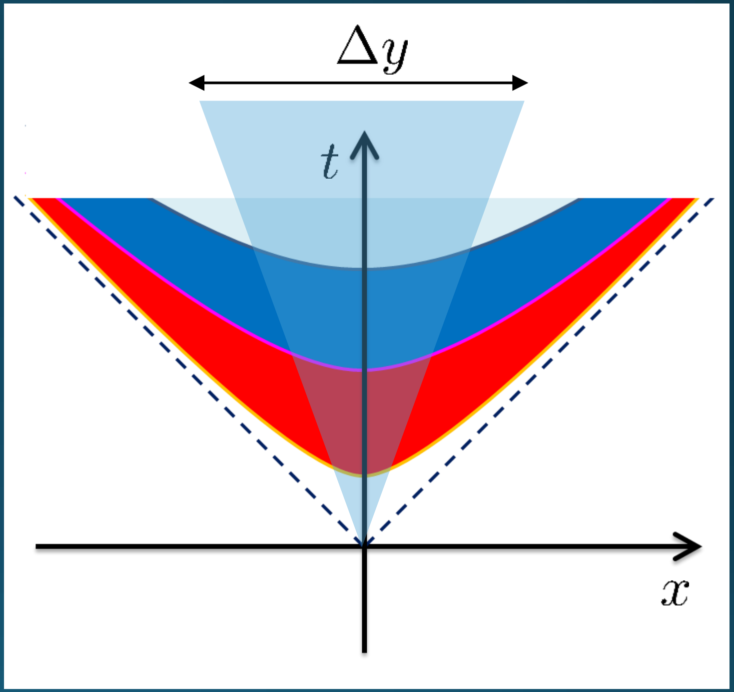


STAR Collab.
2010~

Enhancement & Suppression of non-Gaussian cumulants! → Have we observed QCD critical point?

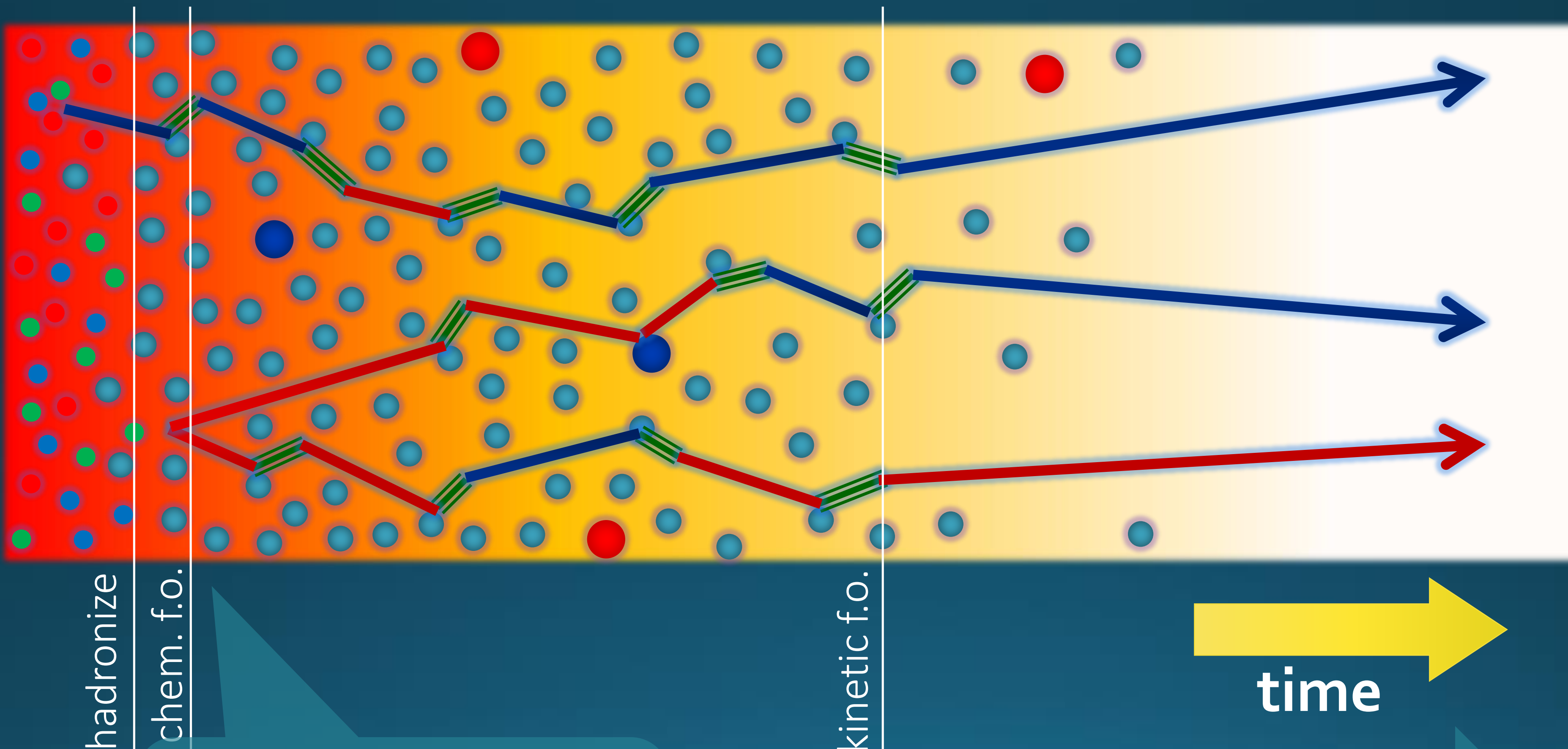
Rapidity Window Dependence





- ☐ Non-Gaussian Cumulants have been observed as a function of rapidity window Δy.
- ☐ Some results have non-monotonic Δy dependence.

Diffusion of Non-Gaussian Fluc.

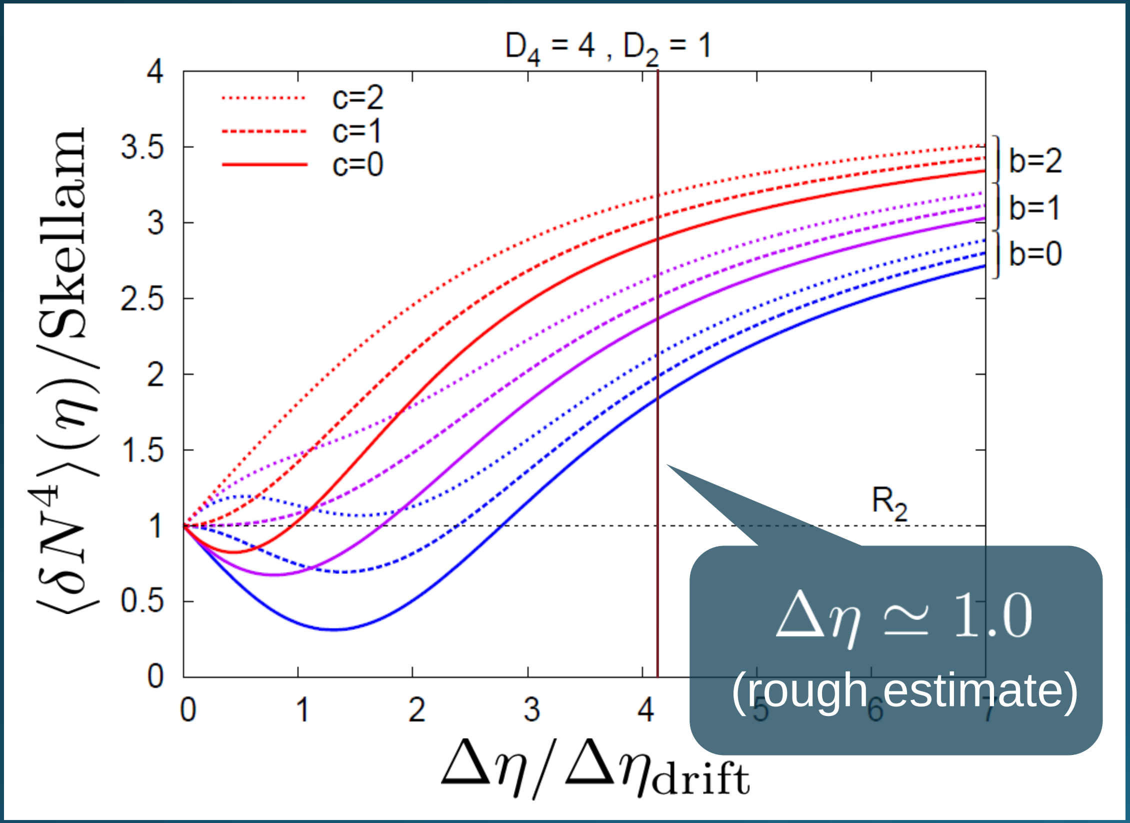


We want to see fluctuations around phase transition

But, fluctuations are modified due to diffusion before observation

Rapidity Window dependence
as a Result of Diffusion

MK (2015)



Parameters

$$D_4 = \frac{\langle Q^4_{\rm (net)} \rangle_c}{\langle Q_{\rm (tot)} \rangle} = 4$$

$$D_2 = \frac{\langle Q^2_{\rm (net)} \rangle_c}{\langle Q_{\rm (tot)} \rangle} = 1$$

$$b = \frac{\langle Q^2_{\rm (net)} Q_{\rm (tot)} \rangle_c}{\langle Q_{\rm (net)} \rangle}$$

$$c = \frac{\langle Q^2_{\rm (tot)} \rangle_c}{\langle Q_{\rm (tot)} \rangle}$$

- Higher order cumulants can behave non-monotonically.
- $\Delta\eta$ dependence encodes history of time evolution.

Rapidity Window dependence
as a Result of Diffusion

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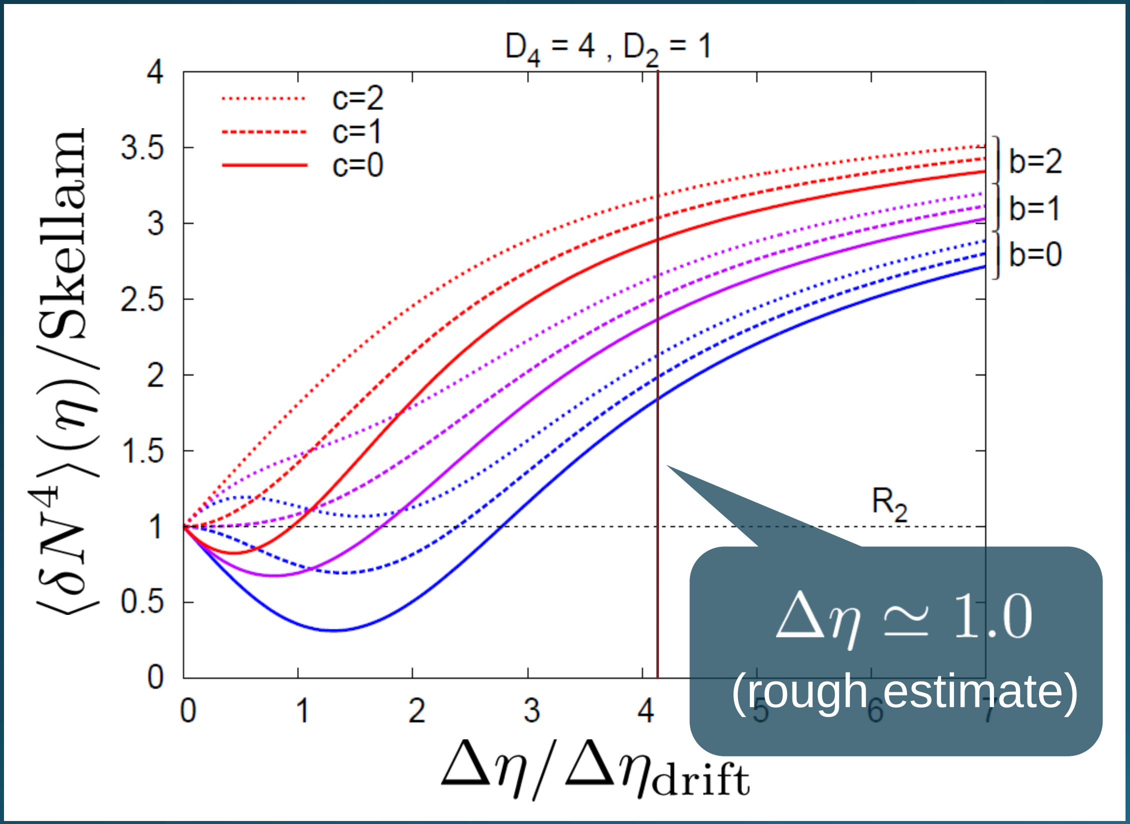
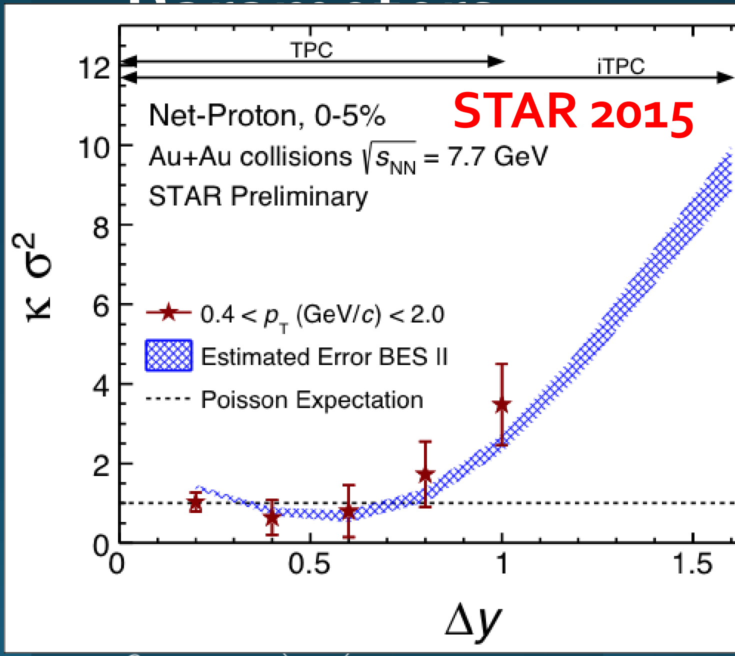


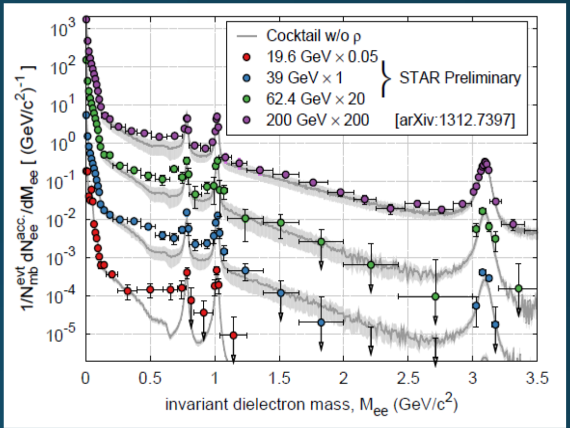


- Higher order cumulants can behave non-monotonically.
- $\Delta\eta$ dependence encodes history of time evolution.

Various Observables

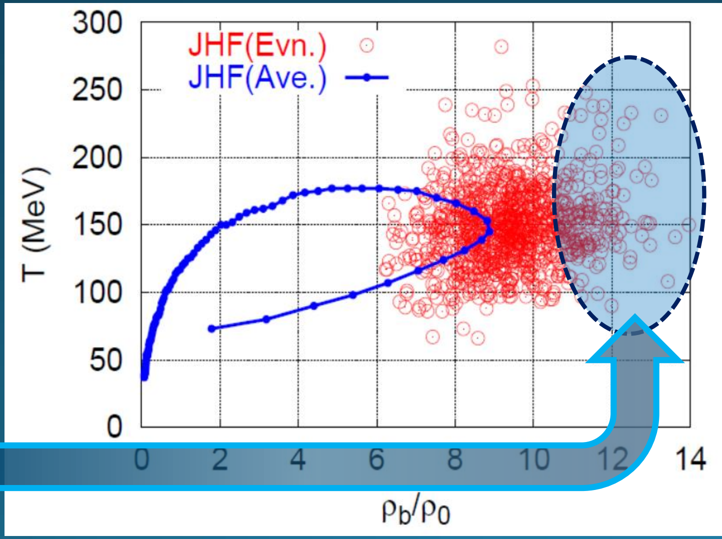
- Flow
- Dilepton / photon
- Fluctuations, higher-order cumulants
- Ξ, Ω, …

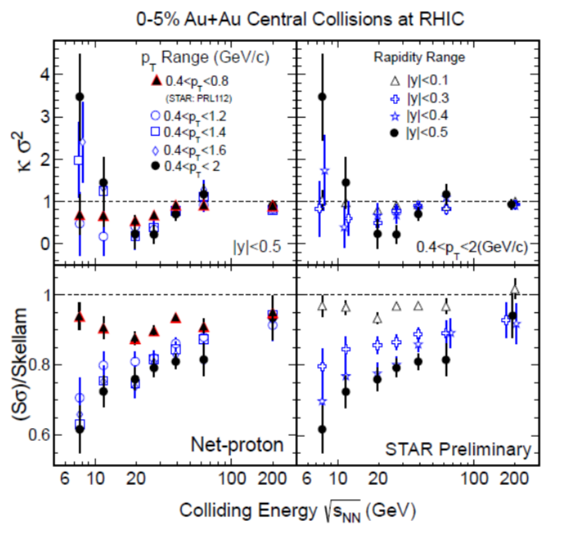
- Sophisticated event selections
- Various correlations



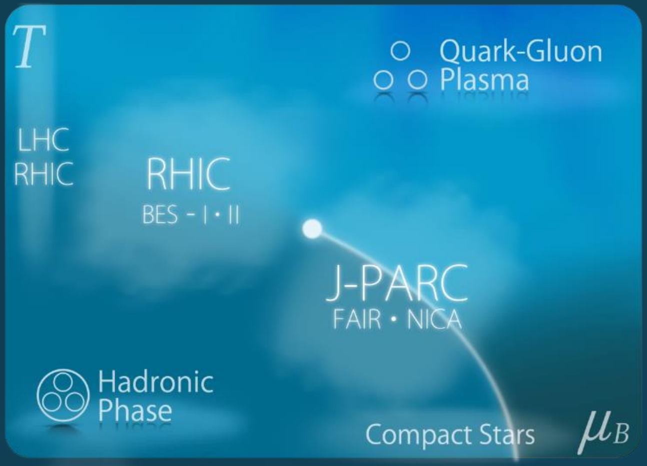
Can we select these events??

MK, Sakaguchi, Sako, Nara, Ohnishi, …





2 Main Goals



Exploring Dense Medium

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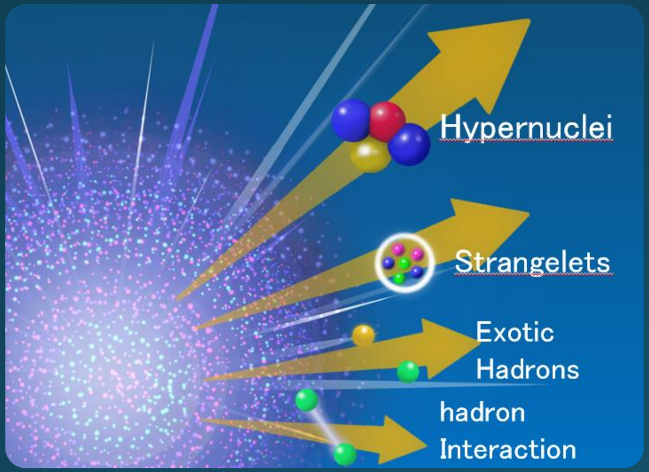
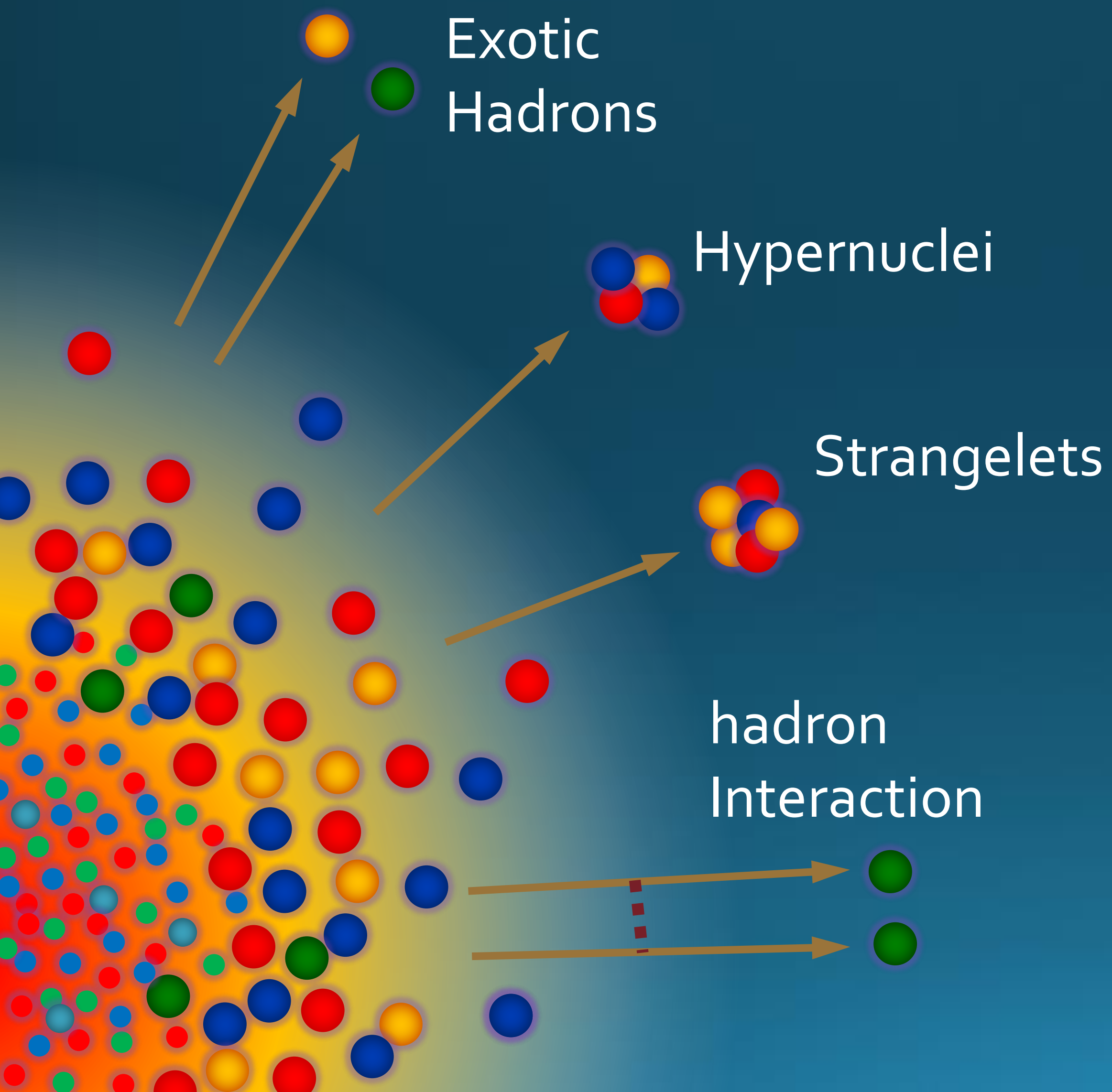


Rare-event Factory

- hyper nuclei
- exotic hadrons
- hadron interaction

Search of Rare Events



- High density
- High luminosity
- High strange yield

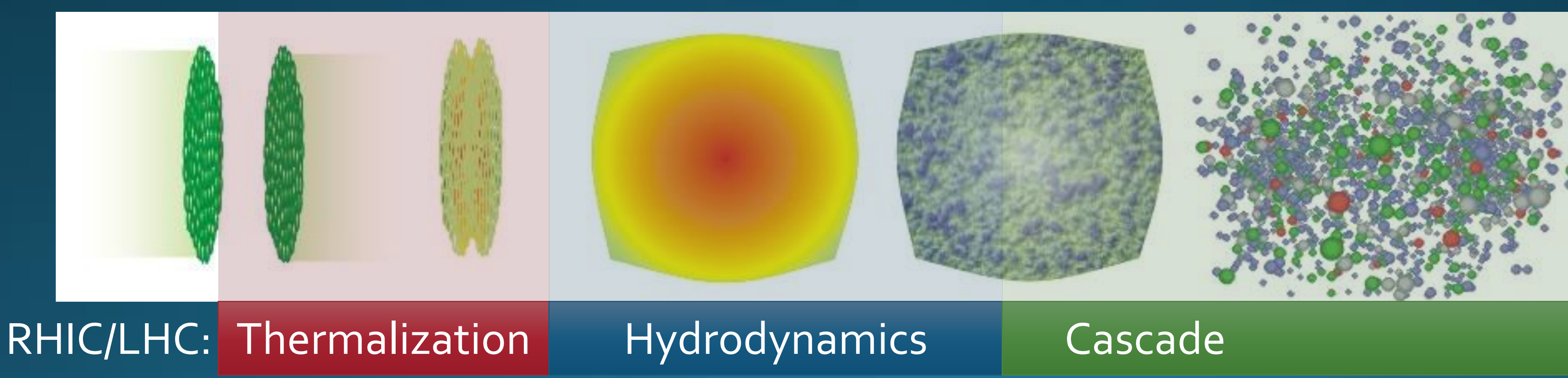
Rare-event Factory

- creation
- properties
- interaction

Theoretical Challenges

RHIC / LHC

- ☐ creation of QGP
- ☐ hydro. models
- ☐ early thermalization
- ☐ (boost invariance)



Theoretical Challenges

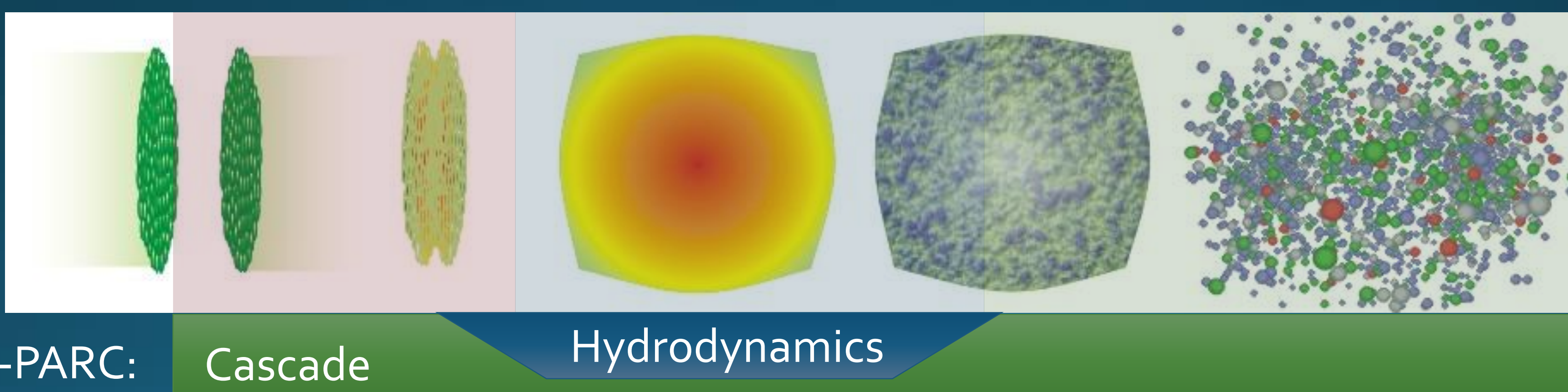
RHIC / LHC

- ☐ creation of QGP
- ☐ hydro. models
- ☐ early thermalization
- ☐ (boost invariance)

Low-E Collisions

- ☐ Initial condition?
- ☐ Thresholod of QGP formation
- ☐ "Integrated" approach
  - Hydro x Cascade

J-PARC:

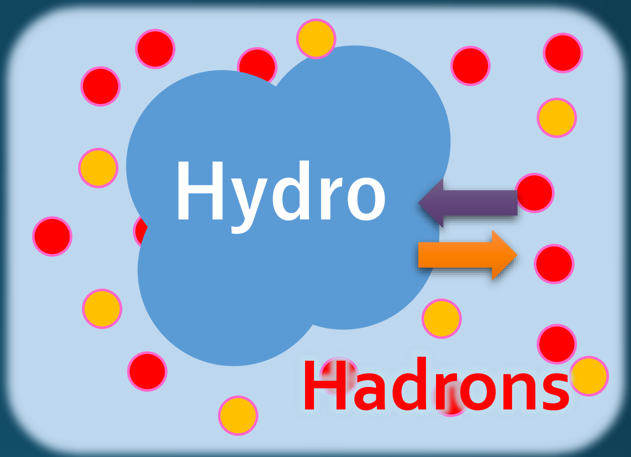


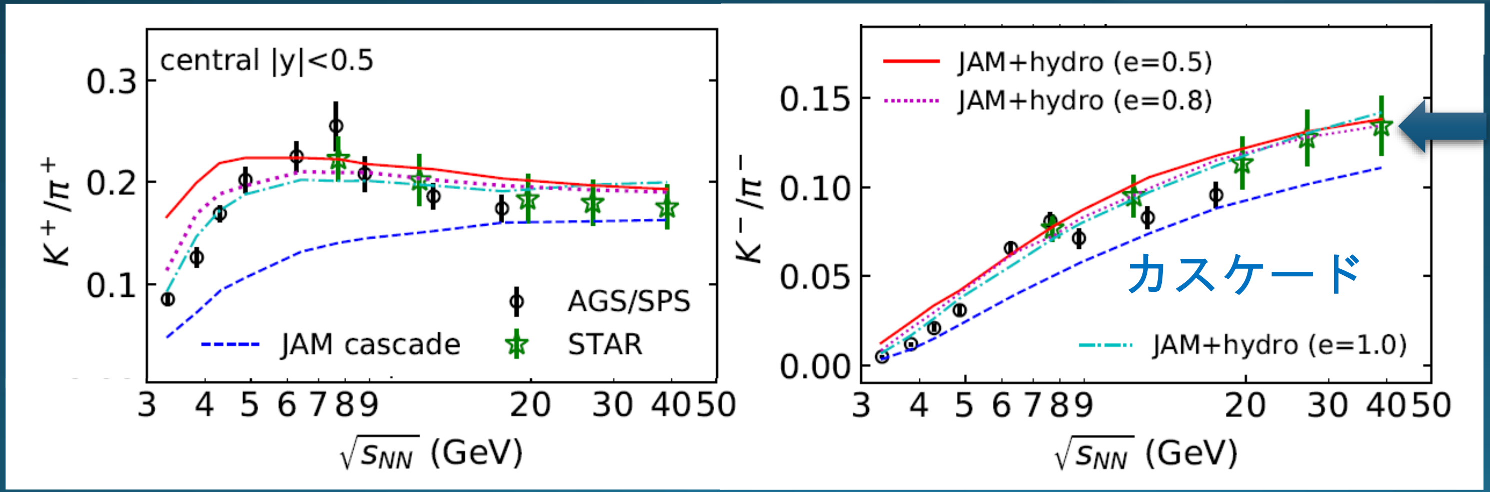
Hydro+JAM Integrated Model

Akamatsu, ..., **Nara**, et al. PRC98 (2018)
Murase, Tuesday F-2

Hydro+Hadron simultaneous time evolution

- ☐ Dense hadrons →Hydronize
- ☐ Cooled hydro →Hadronize

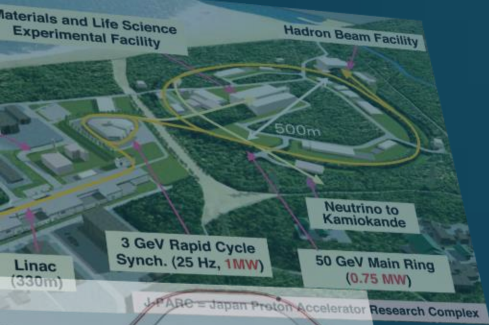


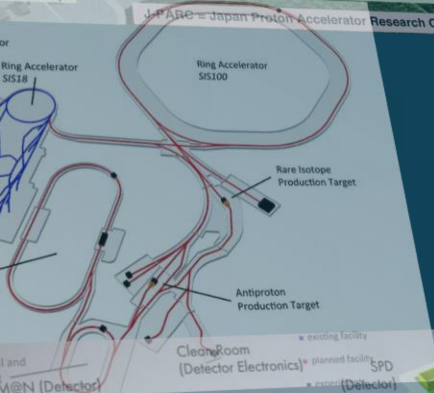


NEW
Integrated

Particle ratio is well described!

Summary





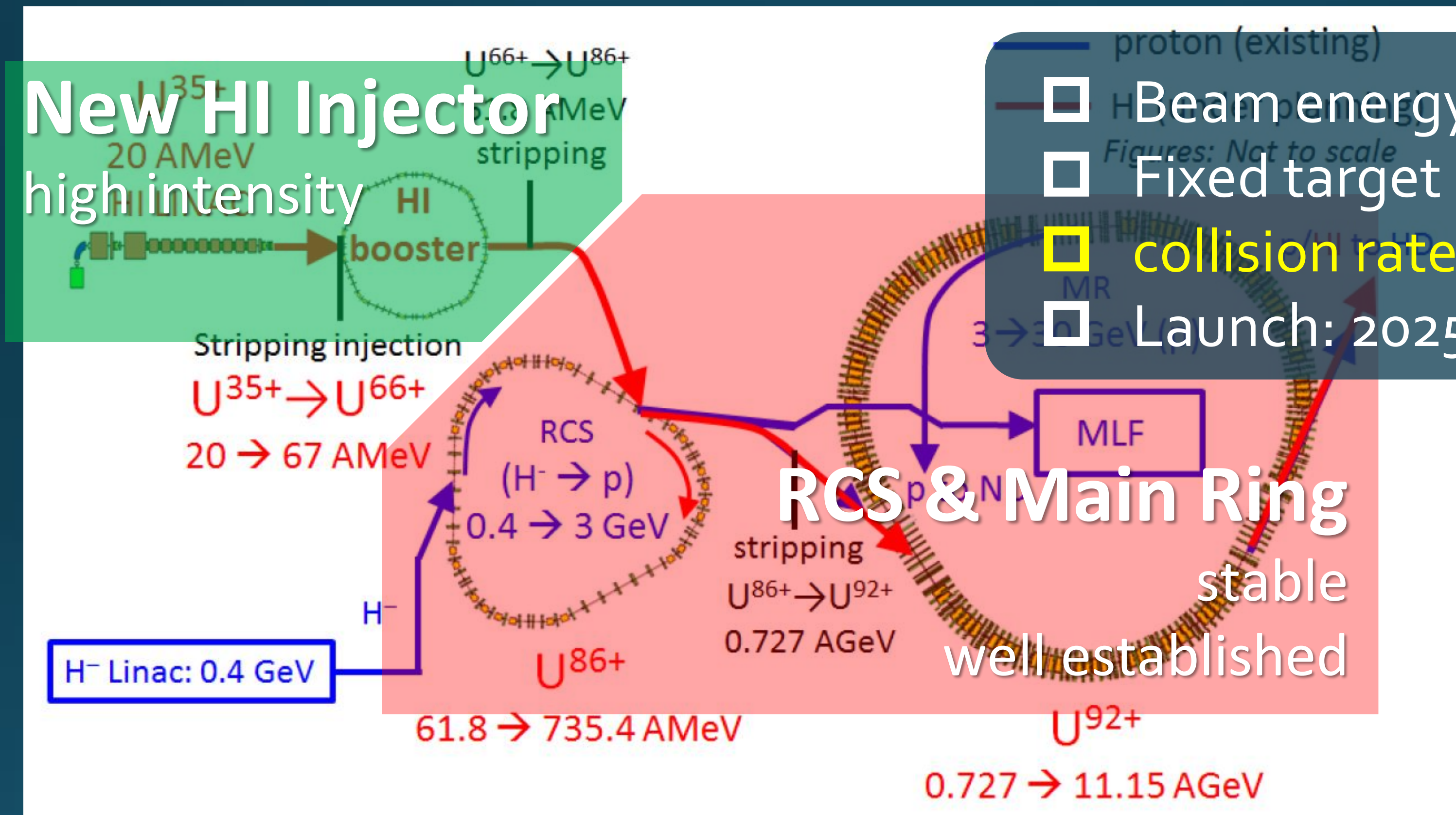
- Exploring dense medium in relativistic heavy-ion collisions is one of the hottest topics in this field. Many new experiments will start in the near future!

- Fluctuations are promising observables for the search for the phase structure of QCD.

- Studies of hypernuclei and exotic hadrons are other important subjects in the future heavy-ion experiments.

J-PARC Heavy-Ion Program

H. Sako, this afternoon (E-3)



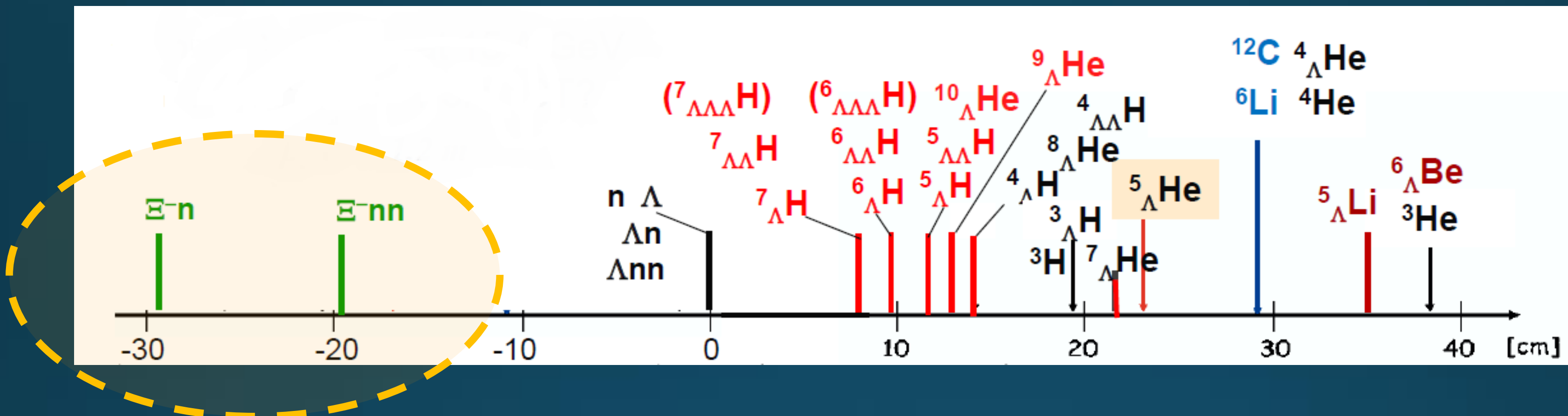
- Beam energy: ~19GeV/A
- Fixed target exp.
- collision rate ~10^8Hz
- Launch: 2025~?

- Utilize reliable / high-performance RCS & main ring
- →Reduce cost and time

http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

backup

Hyper-Nuclear Phyics @ J-PARC

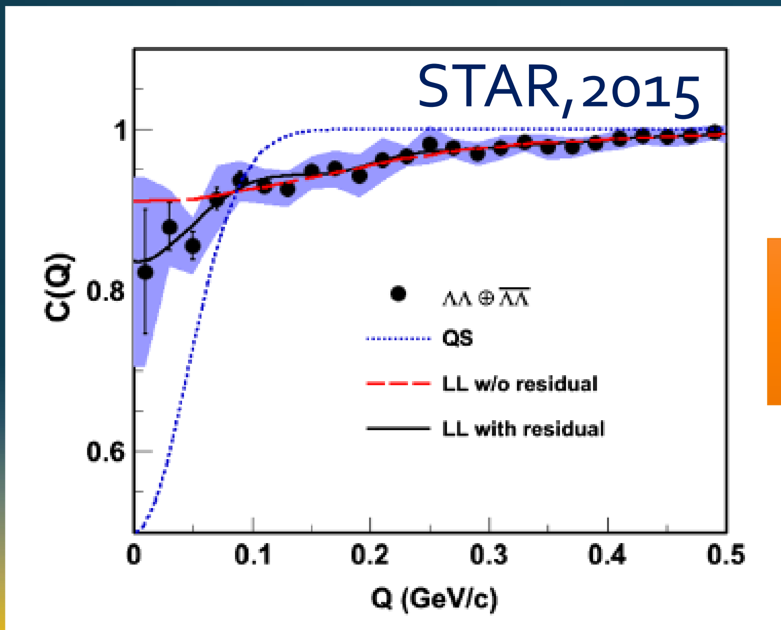


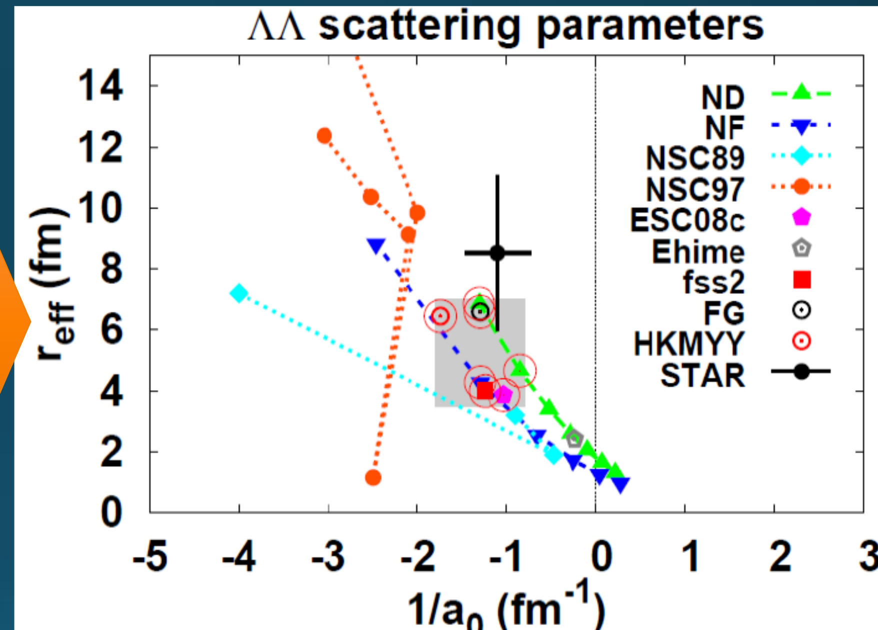
- ☐ Negatively-charged hypernuclei ($\Xi^{-}n$, $\Xi^{-}nn$, …)
- ☐ Nuclear strangelets
- ☐ n-rich / p-rich hypernuclei

- ☐ Measurement of magnetic moments

Hadron-hadron Interaction

ΛΛ Correlation function





Hadron interaction can be studied from correlation function.

emission source func. + relative wave func.

Morita, Furumoto, Ohnishi, 2015

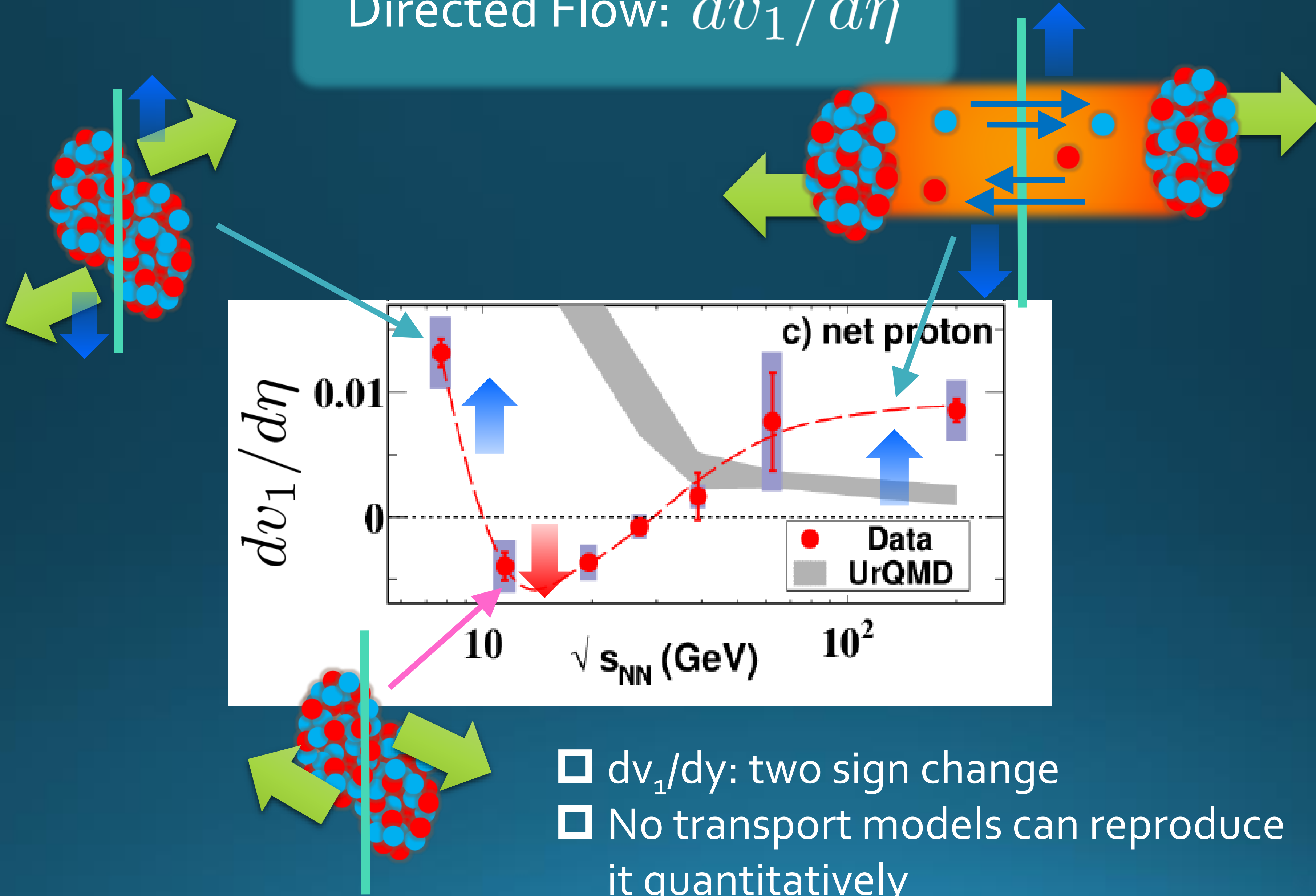
Radial Flow

$$dv_1/d\eta$$

① $dv_1/d\eta > 0$

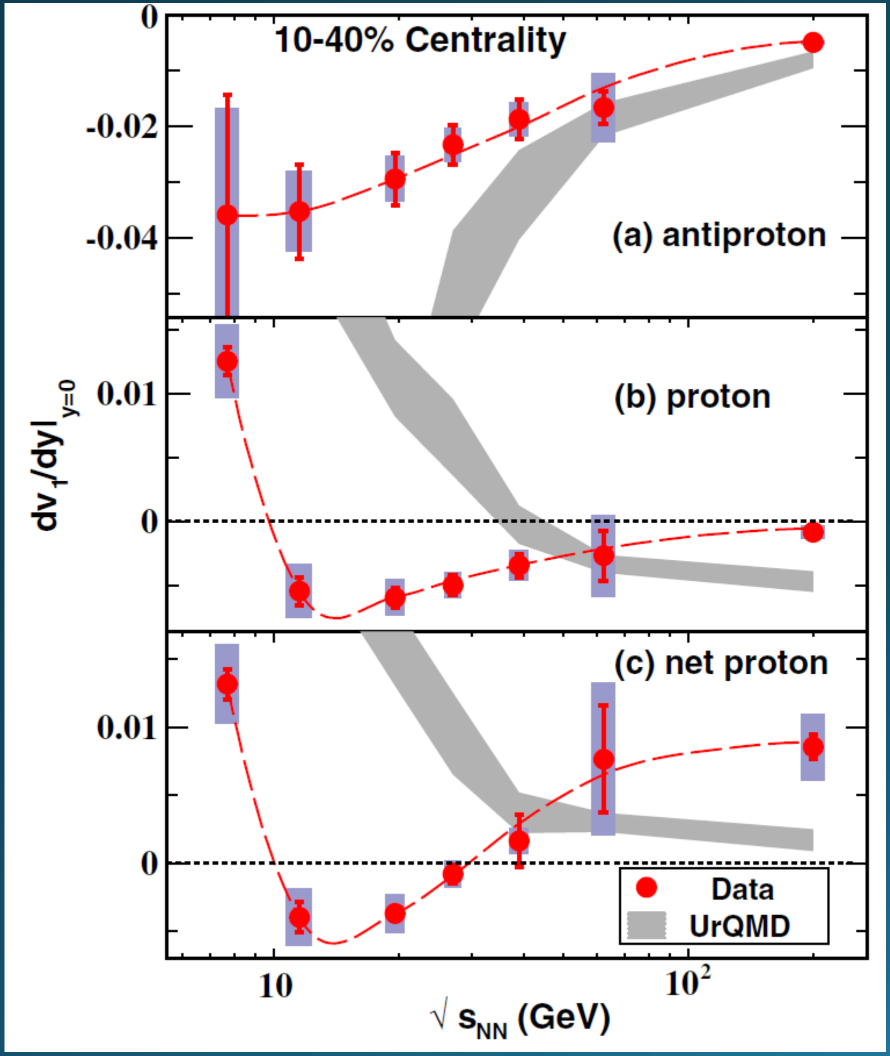
② $dv_1/d\eta < 0$

Directed Flow: $dv_1/d\eta$

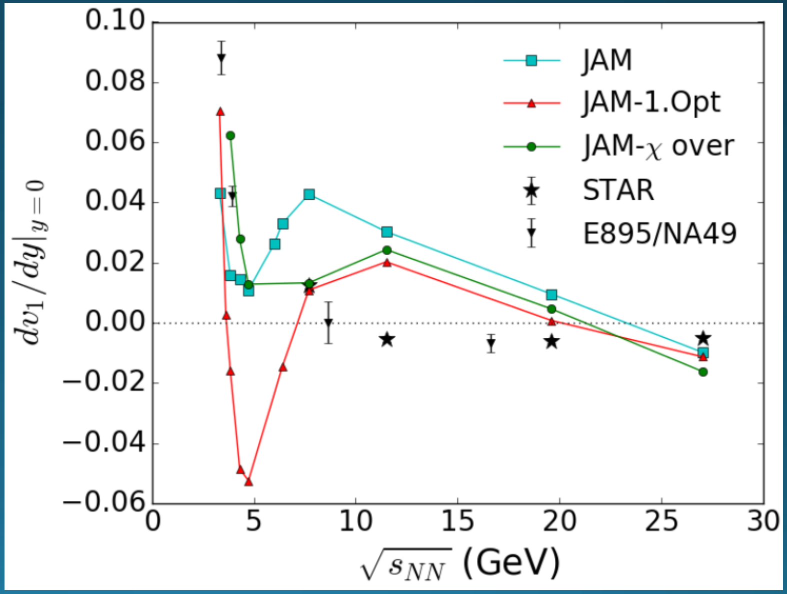


- ☐ dv_1/dy: two sign change
- ☐ No transport models can reproduce it quantitatively

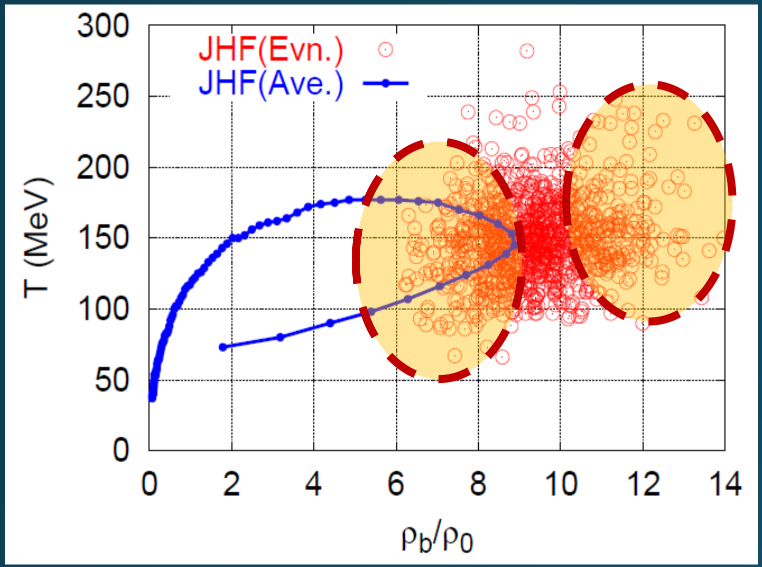
dv_1/dy: Signal of 1st Phase Tr.?



Negative v_1
= signal of softening
≅1st order transition??

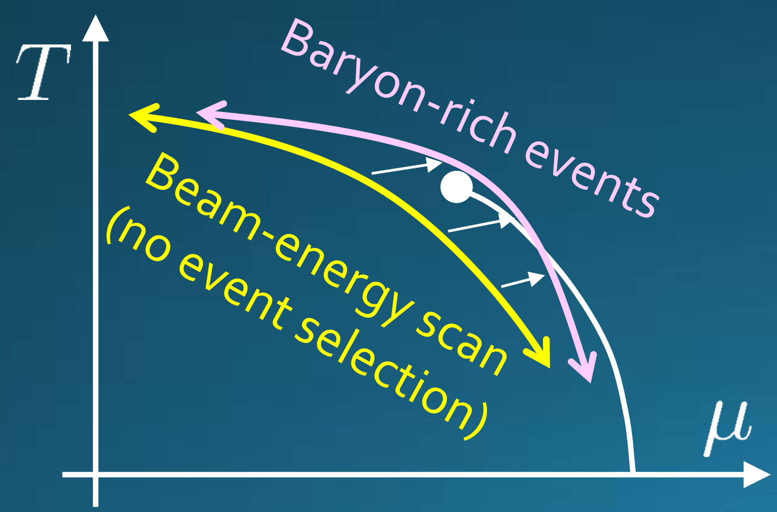


Maximum Density Scan?

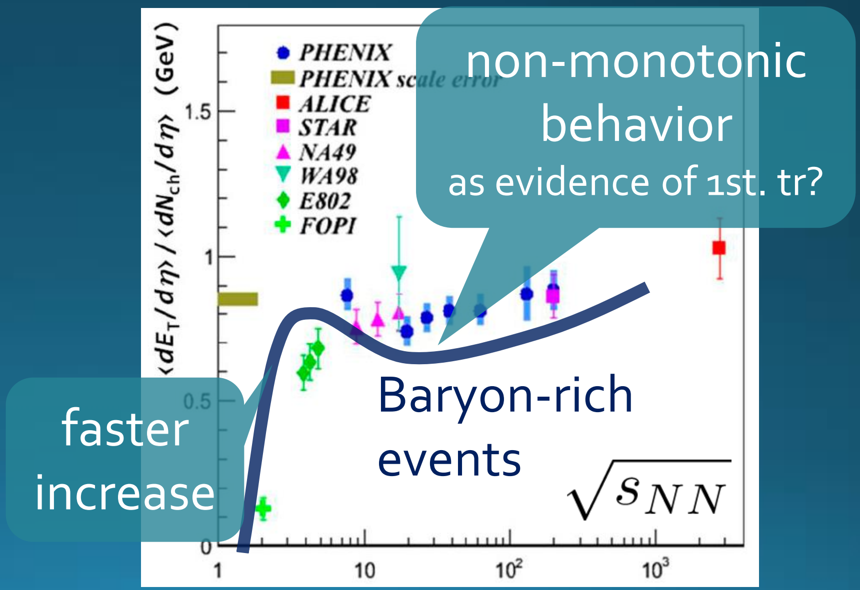


Large event-by-event fluctuations even with fixed centrality.

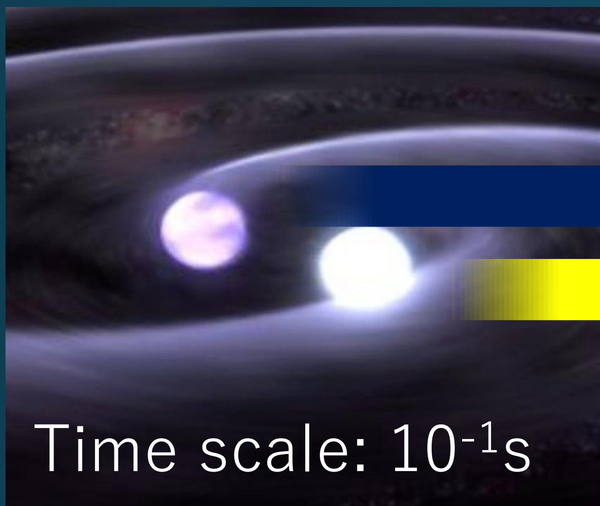
"Maximum density" dependence may be studied experimentally.



average transverse energy

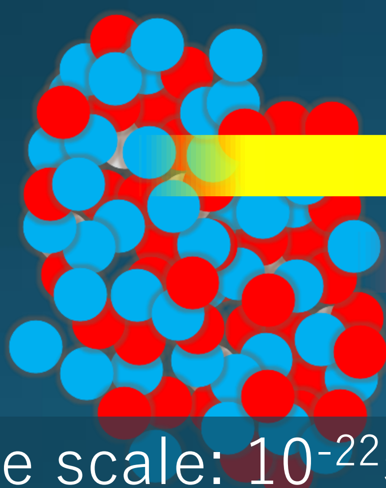


Lepton & Photon: Hierarchical Observation



gravitational wave

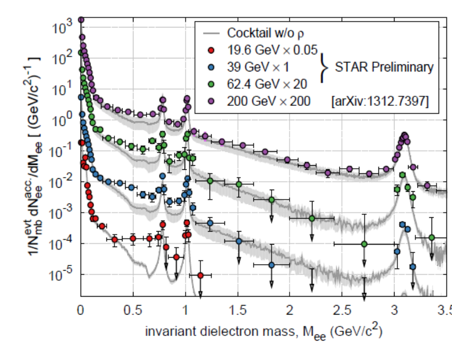
photons



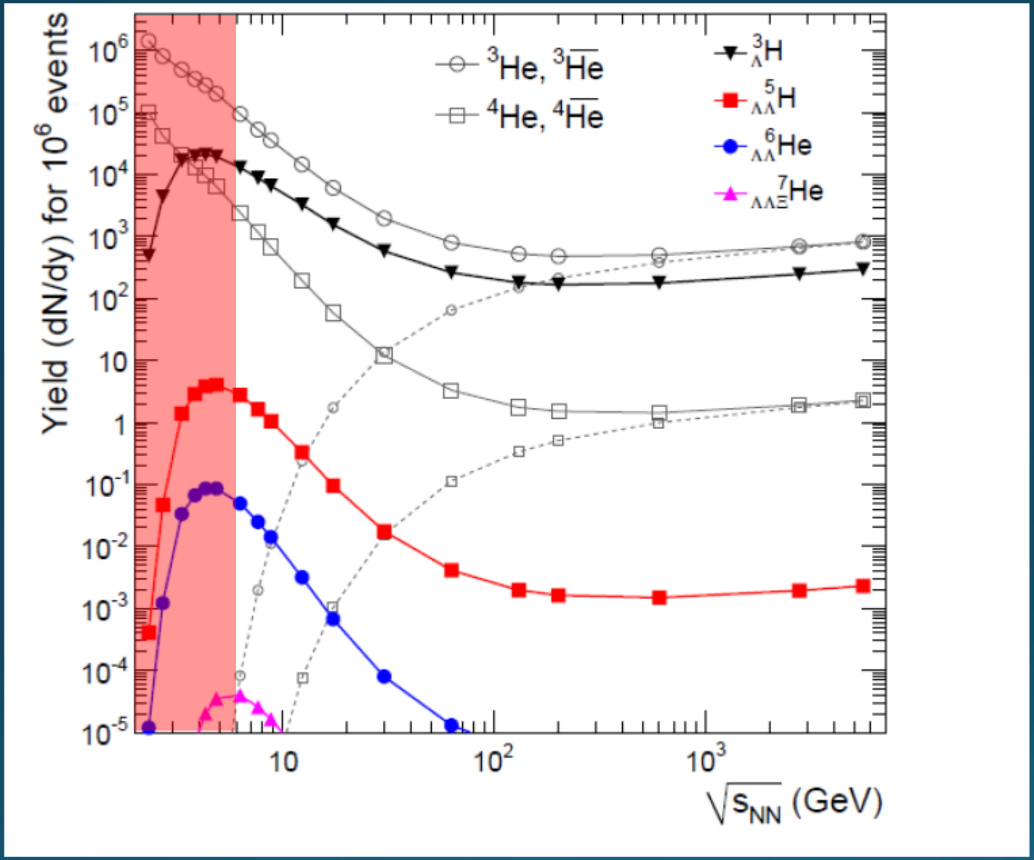
EM probes

hadronic observables

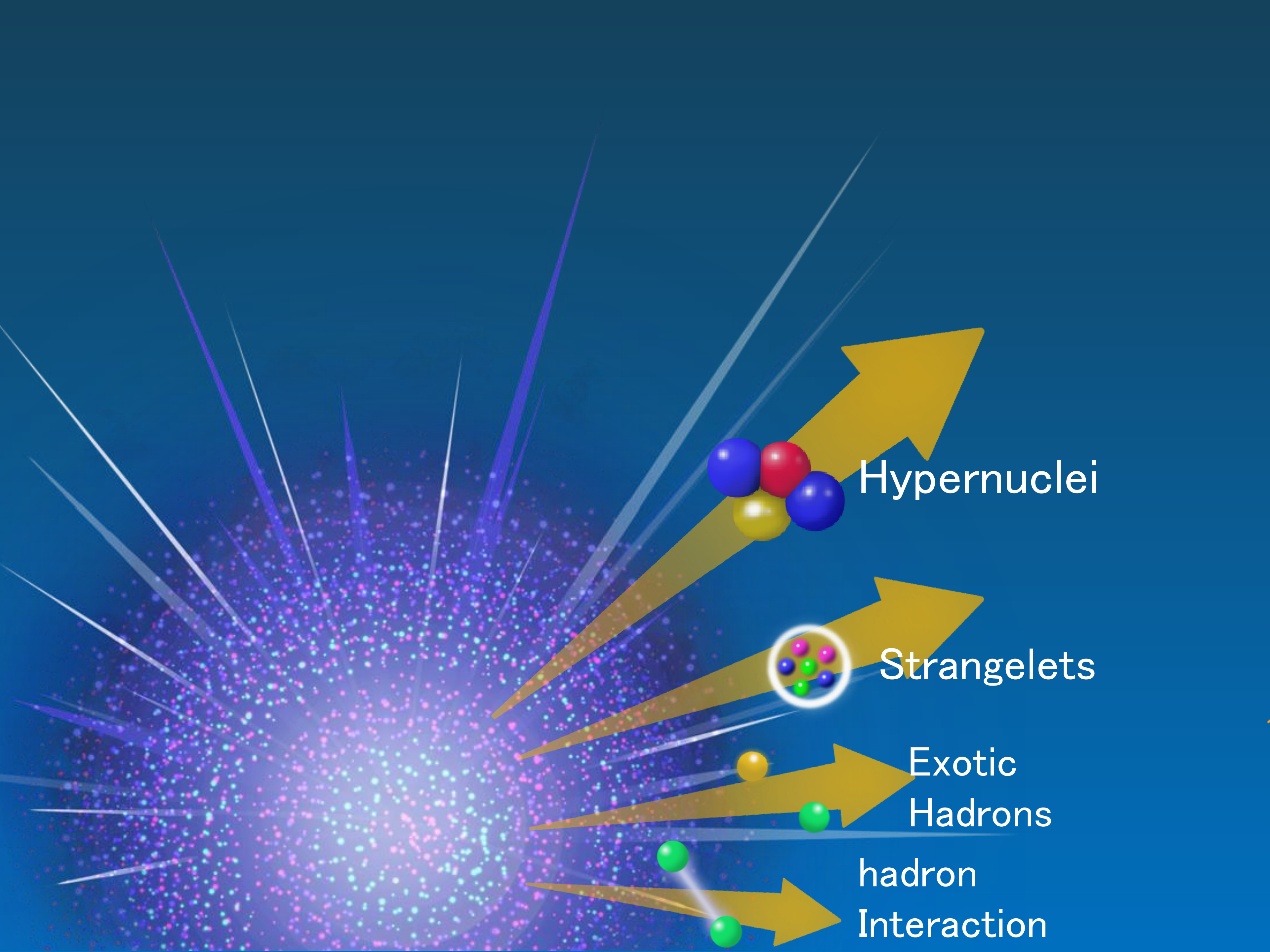
di-lepton yield



Strangeness Factory



Particle yields having strangeness have maximum at J-PARC energy


Hypernuclei
Strangelets
Exotic
Hadrons
hadron
Interaction